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A DESCRIPTION OF WEATHER AND FORECASTING IN THE TROPICS

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This report describes the climatological features, local controls, and some of the synoptic systems that exist in the Tropics. These meteorological details are part of the development of a single-station expert forecasting system for the Tropics. An extensive literature search accomplished in the past year is reviewed. A new model for forecasting tropical disturbances, considering them to be composed of an upper cold low or trough and a surface wave-like disturbance, is proposed. Areas to cover next year are given. The Appendix gives tropical weather characteristics that are of interest to the single-station forecaster.

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1. INTRODUCTION

1.1 Purpose

The purpose of this project is to develop an expert system that will produce short-range weather forecasts of primary meteorological variables and events for the Tropics. Tropical weather cannot be predicted with synoptic models developed in mid-latitudes because:

- prevailing winds in the Tropics are from east to west instead of from west to east
- there are no real changes in air masses so the Norwegian cyclone model cannot be used
- the geostrophic relationship between wind and pressure breaks down near the equator.

A new forecasting system has to be developed in order to predict weather in tropical regions.

This report describes the large scale environment found in the Tropics, the local circulations that dominate weather at a station, and the synoptic systems that change the weather. Section 8, the Appendix, contains characteristics of tropical weather that are of interest to the single-station forecaster.

1.2 Definition of "the Tropics"

In developing this system, the area covered by "the Tropics" first needs to be defined. Definitions include:

- the area between the Tropics of Cancer and Capricorn (the "Torrid Zone")
- the area between 30°N and 30°S
- the area enclosed by the 20°C mean annual isotherm
- the area where there is a heat surplus in the earth-atmosphere system
- "that part of the world where atmospheric processes differ decidedly and sufficiently from those in higher latitudes" with the boundary being that line between easterly and westerly winds at 700 mb (Riehl 1979); in other words, the area between the subtropical ridge axes.

Although the last three definitions are attractive, because they more accurately describe the areas affected by tropical weather, the latitudes they describe can range from 15° to 45°. For the sake of simplicity, it has been decided to define the Tropics for the expert system as the area between 30°N and 30°S. However, the forecaster needs to remember that mid-latitude weather occasionally intrudes into the Tropics and that tropical weather often affects mid-latitudes.

1.3 Why Are the Tropics Important?

Why is forecasting the weather in the Tropics considered to be important? A first argument is that climatology, the original forecasting tool used by tropical meteorologists, fails to predict weather events, such as tropical cyclones and dry periods during wet monsoons, that threaten people and agriculture. Secondly, the Tropics are important from a geographical and meteorological standpoint. For the geographer, the Tropics cover approximately one-half of

the earth's surface area. For the meteorologist, the Tropics provide a significant proportion of the energy needed to drive the atmospheric circulation. Evidence also shows that the El Niño phenomenon, a major factor in interannual variability in weather, has its roots in the Tropics. A third reason is political. Most of the world's developing countries, such as Indonesia, India, and Brazil, are in the Tropics. The primary source of the world's oil supply, the Middle East, is in the Tropics. In the 1990's, the United States has already deployed its military twice in the Tropics, during the Persian Gulf War and in the Somalia operation. Because tropical weather cannot be forecast with mid-latitude models nor with a pure statistical model such as climatology, and because the Tropics are important from a geographical, meteorological, and political standpoint, a weather forecasting expert system designed specifically for the Tropics is needed.

1.4 The Forecasting Problem in the Tropics

Tropical weather is considered to be difficult to forecast. López (1948) stated the common problems:

> *Because of the existence of a relatively homogeneous air mass, pressure and temperature changes in the tropics are small and do not readily lend themselves to the standard methods of analysis used in middle latitudes. In addition, there are relatively few radiosonde stations, and those that do exist are spaced quite far apart. ... Finally, the diurnal variations are very large, making it difficult to interpret comparisons of the morning raob with the afternoon raob or to use 12-hour changes.*

There is also a lack of well-defined synoptic models for tropical weather. The only tropical synoptic system that has been studied in great detail is the tropical cyclone, which affects less than one tenth of one percent of the Tropics on an average day (Ramage 1995). On the other hand, textbooks continue to use Simpson's (1952) statement that North Atlantic subtropical cyclones occur most often in November and January, even though the National Hurricane Center has recorded twelve subtropical cyclones (wind speeds greater than 18 m/sec) in August versus five in November during the period 1970-1994. Another problem is that "typical" tropical weather characterized by warm daytime temperatures, a brief afternoon shower, and a cooling breeze off the ocean is not commonly found over large areas of the Tropics. The Tropics contain the earth's most arid regions as well as the rain forests. Over 60% of Trewartha's (1961) "problem climates," those regions that do not have the expected climate for their location, are in the Tropics.

Two of the biggest problems in forecasting tropical weather are that:

- surface pressures, temperatures, dew point temperatures and winds tend to be dominated by local effects
- the lower atmosphere and upper atmosphere are usually uncoupled.

Surface pressure variations are often due to topographic features and the semi-diurnal pressure wave, meaning that three-hour pressure tendencies are practically useless. Temperature variations due to convection and land-sea breezes are generally much larger than temperature changes due to synoptic influences. In many areas, the diurnal pressure and

temperature ranges are larger than the annual ranges. Because there is little discernible change in air masses, dew point temperatures are not useful as indicators of synoptic changes. Surface winds are also more influenced by local effects, such as the sea breeze, rather than by synoptic systems. The problem of atmospheric uncoupling can be best seen with the tropical cyclone, where an intense low exists at the surface while an anticyclone is present in the upper atmosphere.

1.5 Why an Expert System to Forecast Tropical Weather Will Be Useful

How will an expert system help in the tropical forecasting problem? Because the forecaster trained in mid-latitude weather finds tropical weather to be alien at first, an expert system written specifically for tropical weather will both aid and teach the forecaster. Those who are versed in tropical weather but are accustomed to relatively large amounts of data, such as satellite images, will find the expert system helpful when they have limited data. For those who believe that tropical weather can only be forecast with a persistence and climatology approach, an expert system will aid them in identifying the local and synoptic conditions that make weather. The expert system will "squeeze" as much information as possible out of the available data by using single-station forecasting techniques, tropical synoptic models, and an extensive climatological base. Tropical weather forecasting is neither as easy nor as difficult as many make it out to be. This expert system will aid in taking some of the mystery out of tropical forecasting.

1.6 Information Necessary to Initialize the Expert System

In preparing a station forecast, meteorologists need to have certain information available:

- the current weather situation
- the station average of weather elements over the long-term
- what features of the planetary circulation affect the station
- the local terrain around the station and any circulation associated with it
- the types of synoptic weather systems that can be expected to pass through the station.

The current weather parameters aid in preparing a persistence forecast. Climatology, the long-term average, lets the forecaster know what the "usual" weather is and prevents improbable forecasts. The planetary circulation features influence the gradient flow over the station. The local circulations are the biggest factor in the diurnal cycle of winds, temperature, and precipitation. The synoptic systems change the "usual" weather, mostly in small ways, but sometimes in dramatic ways. The remainder of this report outlines the major elements that go into preparing a short-term forecast for a tropical station.

2. PERSISTENCE AND CLIMATOLOGY

2.1 Persistence

The first forecast "guess" of what the weather will be has traditionally been persistence, that "the future weather condition will be the same as the present condition" (Huschke 1959). Persistence forecasting is well suited for trade wind regions because the gradient flow there is the steadiest on earth. However, pure persistence forecasting tends to fail for surface forecasts of a few hours past present time, if only because temperature and pressure have a well-defined diurnal cycle. Persistence also fails to take into account the local circulations that can influence the surface flow in such a way that there can be a 360° change in wind direction at a station during a 24-hour period. Persistence is more successful in forecasting upper-level winds and temperatures because they are not as sensitive to the diurnal cycle as their surface counterparts are.

2.2 Climatology

The long-term averages of meteorological parameters are known as climatology. Climatology generally makes a better forecast than persistence, especially when the averages are compiled for a small area and stratified by time of day and season, because it contains information both about the large-scale features and the local circulations affecting the station. Meteorologists first thought of the tropical forecast as a climatology problem that would be resolved when a long enough series of observations had been taken over the Tropics (Palmer 1951).

In single-station forecasting, the climatological averages are most useful if they have been compiled for the station in question. Monthly averages of maximum and minimum temperatures, surface pressure, precipitation amounts, and rain and thunderstorm days help the forecaster determine the character of the annual cycle. Hourly averages of meteorological parameters for each month give the forecaster the picture of a "typical" day at the station. For example, hourly surface pressure averages show the semi-diurnal pressure wave, which the forecaster can subtract from the actual pressures in order to determine the true pressure tendency. Hourly precipitation averages let the forecaster know the time of day when rain produced by local effects is most likely to occur. The diurnal temperature cycle, highlighting the time when the maximum and minimum temperatures usually take place., is seen with the hourly temperature averages.

There are several general tropical climatology resources available. Global monthly resultant gradient-level winds have been prepared by Atkinson and Sadler (1970). Sadler (1975) has drawn global monthly streamline and isotach analyses for the upper troposphere. One of the most referenced papers in tropical meteorology is Jordan's (1958) compilation of mean soundings in the West Indies. Mean tropical soundings for the western North Pacific are found in Bell and Kar-sing (1973) and Gray et al. (1975). Tropical cyclone soundings have been calculated by Sheets (1969) for the North Atlantic, Bell and Kar-sing (1973) for the western North Pacific, and Keenan and Templeton (1983) for Australia.

2.3 Using Persistence and Climatology as a Forecasting Tool

Because weather tends to persist in the short term and to return to its climatological mean after being perturbed, meteorologists often combine persistence and climatology in making a forecast. This technique is well suited for the Tropics. As pointed out earlier, the air mass over a tropical station does not change as it does over a mid-latitude station. Wind direction and speed, especially in the trade wind and monsoon regions, are persistent. For forecasting winds above the boundary layer, Ramage (1995) recommended using a vector average of the current wind (persistence) and the climatological wind "unless the evidence for [not] doing so is very strong." Fitzpatrick et al. (1995) suggested using different combinations of persistence and climatology, depending on the direction and speed of the observed wind, to forecast 200 mb winds over the Caribbean.

A persistence and climatology approach to forecasting tends to succeed because the Tropics have, in general, well-defined seasons. The "wet" season, usually the time of high sun, is when the majority of the annual precipitation occurs. The "dry" season, usually the time of low sun, is when little precipitation falls. The "transition" seasons are the periods, lasting about a month each, between the wet and dry seasons. Forecasts based on persistence and climatology have the best chance of success during the middle of the wet and dry seasons when the large-scale circulations are established. Persistence and climatology forecasts are usually not successful during the transition seasons when the large-scale circulations are changing, or during the period when a synoptic system is affecting the station. It is these situations that challenge the tropical forecaster because people need to know what the weather changes will be and how it will affect them.

3. LARGE-SCALE FEATURES

3.1 Subtropical Highs

The Hadley circulation is responsible for transporting atmospheric energy from the equatorial region to the mid-latitudes. It is a direct circulation with rising, convergent air near the equator and descending, divergent air near 30°N and 30°S. The subtropical highs formed by this descending branch mark the zone of transition between the mid-latitude westerlies and the tropical easterlies. The highs are not static and stationary, but change position with the sun. For example, the Azores high in the North Atlantic has a mean position of 30°N 35°W in Northern Hemisphere winter and 35°N 40°W in Northern Hemisphere summer (Walters et al. 1989). The subtropical highs have both intraseasonal and interannual variability. If a station is directly affected by a subtropical high, the high's strength needs to be monitored for forecasting purposes. For example, when a high weakens in intensity, polar air is more likely to penetrate into the Tropics.

3.2 Trade Wind Region

The trade winds are the winds that blow from the subtropical highs towards the equator. They are best developed on the eastern and equatorward sides of the highs. The winds are northeasterly in the Northern Hemisphere and southeasterly in the Southern Hemisphere. They are primarily surface winds and are characterized by the greatest constancy of direction and speed on earth. The trade wind region is marked by the trade wind inversion, a temperature inversion that separates tropical maritime air from the warm and dry superior air of the Hadley circulation. Another characteristic is the trade wind cumulus, clouds that form in the maritime air under the trade wind inversion. The height and strength of the trade wind inversion often help in predicting the possibility of precipitation. For example, if the trade wind inversion has a low base and is vertically deep, there is little possibility of major precipitation and trade wind cumulus formation is suppressed. During the wet season, the inversion is usually weak to nonexistent. Some forecasters use the reappearance of a strong inversion as a signal that the transition to the dry season has begun.

3.3 Intertropical Convergence Zone (ITCZ)

The Intertropical Convergence Zone (ITCZ) is that area in the tropics where surface winds from the Northern and Southern Hemispheres meet. Its mean global position is along 5°N. Various definitions have been proposed for the ITCZ, such as the axis of the surface equatorial trough and the zone of maximum cloudiness near the equator, but no one definition has been officially adopted. The nature of the ITCZ changes as it moves away from the equator. Near the equator, roughly 5°N to 5°S, the northeasterly and southeasterly trade winds meet, with convection and precipitation occurring in the convergence zone. However, as the ITCZ moves further poleward, the easterlies on the equatorward side of the ITCZ are deflected due to the Coriolis force and become westerlies, while easterlies remain on the poleward side. Thus, the ITCZ becomes a zone of divergence rather than of convergence. In addition, the major precipitation region shifts to 100-200 km equatorward of the divergence zone instead of occurring in the zone itself (Frank 1983). Because of these differences, some meteorologists have proposed discontinuing use of the term "ITCZ" and using the terms "near-equatorial trade wind convergence" (NETWC) to describe the convergence zone and "monsoon trough" to describe the divergence zone. This project will use these two definitions in order to predict weather in the "ITCZ."

3.4 Monsoon Regions

Monsoon regions are marked by surface winds that reverse their direction between the times of high and low sun. The wind reversal is generated by the differential heating of ocean and land surfaces during the year. The high sun period is usually the wet season. Ramage (1971) has defined the monsoon region as that area with January and July surface circulations in which:

- the prevailing wind direction shifts by at least 120° between January and July
- the average frequency of prevailing wind directions in January and July exceeds 40%
- the mean resultant winds in at least one of the months exceed 3 m/sec
- fewer than one cyclone-anticyclone alternation occurs every two years in either month in a 5° latitude-longitude rectangle.

His criteria are met in the area with the boundaries between 35°N and 25°S and between 30°W and 170°E. Other meteorologists also call Central America and central South America a monsoon region because it is affected by monsoon trough passage (see above) and equatorial westerlies during the wet season. In the Northern Hemisphere, the winds are southwesterly during the wet season and northeasterly during the dry season; in the Southern Hemisphere, the wet season winds are northwesterly and the dry season winds are southeasterly. The beginning and end of the wet season are marked by passage of the monsoon trough. The appearance of the wet monsoon is of great concern to people living in the region because about 75% of the annual rainfall occurs during the wet monsoon. The failure of the wet monsoon often leads to drought and famine.

3.5 Tropical Upper-Tropospheric Troughs (TUTT)

The tropical upper-tropospheric trough (TUTT) is a high sun feature over the North and South Atlantic and North and South Pacific Oceans. It is a sharp, narrow, cyclonic shear zone with a large horizontal tilt and is the axis along which the frequency of upper cold lows is maximum. The TUTT is bounded poleward by the subtropical ridge and equatorward by the subequatorial ridge; this ridge-trough-ridge triplet usually has large meridional displacement during the high sun season. The upper cold lows found in the TUTT have their maximum circulation at 200 mb, coldest temperatures at 300 mb, and rarely extend lower than 700 mb. Maximum convection and precipitation occur in the southeast quadrant (Carlson 1967, Whitfield and Lyons 1992). TUTT lows can aid the development of tropical cyclones by enhancing the upper-level outflow of the cyclone. For example, in 1992 a tropical wave developed into a tropical depression because of interaction with the North Atlantic TUTT and later became Tropical Storm Earl (Mayfield et al. 1994).

4. LOCAL CIRCULATIONS

4.1 Introduction

Local circulations, those that have a period of no more than 24 hours, develop because of differences in local surface heating. These differences arise because land surfaces heat and cool more quickly than water surfaces, because mountain slopes heat and cool more quickly than the surrounding free air, and because the near-surface atmosphere is more responsive to diurnal heating than the upper atmosphere. In the Tropics, synoptic systems rarely suppress local circulations but instead enhance the precipitation associated with them. Therefore, the tropical forecaster must be first aware of the local circulations associated with a station and then determine how the synoptic situation will affect these circulations.

4.2 The Importance of Topography

Topography, which is the height of the terrain, the distribution of land and sea, and the character of the vegetation, determines what local circulations will exist at a particular station. Anabatic and katabatic flows usually do not develop when the terrain is less than 300 m (1000 ft) high. For the sea-land breeze circulation to exist, the water surface near the station needs to be large enough in order to generate the necessary temperature difference. In the Tropics, this water surface does not have to be as wide as the water surface area needed to generate a sea-land breeze circulation in mid-latitudes. For example, a river-land breeze has been observed along the Orinoco River of northern South America (Simpson 1994). The development of a local circulation can be helped or hindered by vegetation. Because dry, barren areas heat up more quickly than moist, well-vegetated ones, the dry areas have more heat available to initiate the local circulation. For example, the sea breeze is practically non-existent along the swampy coastline of the Guyanas of South America (Ramage 1995).

4.3 Factors That Modify Local Circulations

Because there are many mountainous islands and coastlines in the Tropics, forecasters must be aware of how the gradient wind direction modifies local circulations. Estoque (1962) was the first to model the strength and position of the sea breeze according to the direction of the prevailing wind. Kimura (1985) demonstrated that the easterly winds generated by the local circulation in the Tokyo region would overwhelm a light synoptic westerly wind ($\leq$ 3 m/sec). Arritt (1993) calculated that an onshore synoptic flow of greater than 4 m/sec would be enough to suppress a sea breeze, but that a sea breeze circulation would still develop with an offshore synoptic flow of 11 m/sec.

Other investigators have studied the interaction of the sea-land breeze with the anabatic-katabatic flow. Mahrer and Pielke (1977) found that the sea breeze and mountain circulations acted together to produce a more intense circulation than they did when acting separately. Ookouchi et al. (1978) concluded that the inland penetration of the sea breeze front was stopped at the top of the mountain, and that the katabatic wind intensified the land breeze. Kikuchi et al. (1981) showed that, in the Tokyo region, the combined sea breeze-anabatic flow had a three-cell structure along the seaward side of the mountain, and the katabatic flow-land breeze combination began earlier than the land breeze circulation did alone.

Extensive research has shown how mountain blocking, which is a feature in stably stratified flows, decelerates the gradient wind (Smith 1980). (Note that the trade winds are a stably stratified flow.) When the gradient wind is blocked, local circulations, which would otherwise be overwhelmed by the gradient wind, can develop on the windward side of mountains. Blocking can be predicted by calculating the Froude number Fr (equation 1, section 8.3.1), which is a combination of the wind speed, the height of the terrain, and the Brunt-Väisälä frequency. The critical values of the Froude number are (Smolarkiewicz and Rotunno 1989, Lin and Wang 1996):

Froude number	*Effect on flow*
>1.0	no upstream blocking; stationary mountain waves.
0.5-1.0	upstream blocking on windward side; strong downslope winds on lee side.
0.1-0.5	upstream blocking with flow stagnation on windward and leeward sides.
<0.1	negligible gradient wind; thermal forcing is dominant.

In low Froude number regimes ($Fr < 1.0$) the trajectory-integrated thermal forcing η^* (equation 3, section 8.3.1) can affect the upstream blocking. A combination of η^* and Fr (equation 4, section 8.3.1) forecasts whether thermal forcing will dominate terrain forcing (Reisner and Smolarkiewicz 1994). When this combination is less than 1, the upwind flow will always exhibit upstream stagnation during the heating cycle and the flow will always be blocked. When this combination is greater than 1, there will be a critical transition during the daytime heating cycle from a blocked to an unblocked flow regime. When η^* is greater than or equal to 1, the flow will be unblocked regardless of the value of Fr. When the absolute value of η^* is much less than 1, the effects of thermal forcing are negligible. Note that, for larger values of η^*, the lee flow response will be stronger because the lee flow is dominated by thermal forcing.

4.4 Sea and Land Breezes

The sea-land breeze circulation system is a simple thermal circulation arising from the difference in surface temperature between land and a water area. Because of its heat capacity, a large water surface can be considered to be isothermal during the course of a day. In contrast, land has a temperature cycle over 24 hours. During daylight hours, the land mass is warmer than the water. This warmer air leads to the development of a local heat low over the land. Because air flows from high to low pressure, air near the surface moves from water to land and is called the sea (lake, river) breeze. During nighttime hours, the land becomes colder than the water. This leads to development of a local heat low over the water and air moves from land to the water, called the land breeze. Because the temperature contrast and the tropospheric instability are greater during the day than at night, the sea breeze circulation is stronger than the land breeze. For the sea breeze, the boundary between the land air and the water air is known as the sea breeze convergence zone, which is marked by strong upward motion and convective cloudiness. The land breeze may also have a convergence zone that is usually found offshore along the coastline. The sea breeze convergence zone is responsible for the afternoon showers common over tropical islands and coastal regions, and the land breeze convergence zone is responsible for the nighttime showers that occur offshore. Both the sea and land breezes have a downward component that compensates for the upward component in the convergence zone; the sea breeze's component is over the water and the land breeze's component is over land. Because of the Coriolis effect, the sea-land breeze convergence zones will turn to the right (Northern Hemisphere) with time. In the Tropics, the sea breeze is a welcome relief because the cooler air from over the water surface slows or even briefly stops the diurnal temperature rise.

The existence, strength, and position of the sea-land breeze are dependent on:

- the magnitude of the temperature contrast between land and ocean
- the direction and speed of the gradient wind (Estoque 1962, Arritt 1993)
- the shape of the coastline (McPherson 1970)
- the presence of terrain (Mahrer and Pielke 1977, Kikuchi et al. 1981)
- the latitude of the station (Yan and Anthes 1987)
- the width of the land mass (Xian and Pielke 1991).

A sea-breeze index developed by Walsh (1974) predicts how large a temperature difference between land and water is needed to develop a sea breeze for a given gradient wind speed (equation 5, section 8.3.2). It is dependent on the initial temperature of land unaffected by the water mass (T_0) and the square of the wind speed. This index cannot be used for predicting the sea breeze on smaller islands because of the requirement that T_0 be unaffected by the water mass. Note that the index predicts that a sea breeze will not develop for wind speeds greater than 6 m/sec, because the temperature difference required between land and water is larger than the temperature difference that usually occurs.

4.5 Anabatic and Katabatic Flows

Mountains also generate local circulations, called anabatic (upslope) and katabatic (downslope) flows. They are a direct thermal circulation like the sea-land breeze. After sunrise, the air near the sloping ground becomes warmer than air in the free atmosphere at the same height above sea level. A local heat low develops over the sloping ground and the pressure difference between the slope and the atmosphere causes air to move upslope. The reverse happens at night. After sunset, the air near the sloping ground becomes cooler than air in the surrounding free atmosphere. The resulting pressure difference between the slope and the atmosphere causes air to move downslope. Studies have shown that the anabatic-katabatic flow system is more efficient than the sea-land breeze system, requiring less heat input to generate a circulation of comparable size (Atkinson 1981). This means that anabatic (katabatic) flows often start within an hour after sunrise (sunset) rather than the sea breeze's (land breeze's) usual starting time of 1000 LST (0000 LST). Anabatic flow is sensitive to changes in insolation; it is stronger on east slopes in the morning and on west slopes in the afternoon, but any shading causes an immediate response by the wind (Defant 1951). As with the sea-land breeze, anabatic-katabatic flows are sensitive to the speed of the gradient wind. Investigators have not established an upper boundary for which anabatic-katabatic flows do not exist, but most of these flows have been observed with a geostrophic wind speed of less than 6 m/sec (Atkinson 1981).

The rising air of anabatic flow leads to cumuliform cloud formation and showers over isolated peaks and mountain ridges, whereas the cold air drainage of katabatic flow leads to fog formation in the valleys. Both clouds and fog quickly dissipate after the flow that formed them ceases. Interesting cloud formations occur with the interaction of anabatic flow with the sea breeze. Over elevated coastlines and larger tropical islands, such as Puerto Rico and Hawaii, the combination of the sea breeze and the anabatic flow creates large cumulus clouds over the mountainous interior. Meanwhile, the upper-level subsidence of the sea breeze cell

is found offshore, hindering development of trade wind cumulus over open waters. An area (or ring in the case of an island) of clear air is present offshore, with trade wind cumulus again present further upstream.

4.6 The Tropical Rainstorm

As dubbed by Henry (1974), the "tropical rainstorm" is the precipitation that occurs from deep cumulus convection in the Tropics. It occurs on a nearly daily basis during the wet season when synoptic forcing is weak or absent. It is associated with local wind regimes or with convection that happens as a result of the intense radiation, moist air and unstable atmosphere conditions that are common in the Tropics. Many tropical synoptic systems enhance, rather than overwhelm, the tropical rainstorm's precipitation pattern and amount and the local forcing that leads to the rainstorm's development.

In his study of rainfall patterns in Southeast Asia and Central America, Henry (1974) was able to develop a composite rainstorm. A tropical rainstorm has at least 25 mm of rain at its core. Dry season storms are usually smaller in diameter but have an equal amount of rain at their core as wet season storms. A storm's size is about 30 km in diameter and its lifetime is one to three hours. The average spacing from center to center of the storms is 60 km; the chance of rain falling on a station at a distance of 30 km from the center of a storm is greatly diminished. Usually only one rainstorm occurs at one place on any given day.

The time of day that the tropical rainstorm usually occurs depends on the location of the station (Gray and Jacobson 1977). The "normal" late afternoon to early evening rainstorm occurs in:

- continental areas with clear skies in morning and sufficient moisture (radiative heating)
- islands and regions of elevated terrain
- windward sides of mountains
- leeward sides of large islands and peninsulas
- oceanic ITCZ's.

Areas that have a night to early morning maximum in deep convection and precipitation include:

- continental areas with cloudy skies in evening and sufficient moisture (radiative cooling)
- areas with a low-level nocturnal jet
- windward sides of large islands and peninsulas
- valleys where mountain winds are blowing in opposite direction to gradient wind
- coastal areas
- wet monsoon regions
- open ocean regions away from the ITCZ
- regions experiencing an intense organized synoptic system.

The windward side of the island of Hawaii is a good example of how diurnal rainfall patterns can change over a small area because of location. Chen and Nash (1994) showed that the slopes have a rainfall maximum in the afternoon, the offshore areas have a maximum during the night, and the coastal areas have a maximum in the morning.

Conditions that limit diurnal convection include extensive cloudiness, rain within the previous 12 hours, and a low trade wind inversion base with a deep dry layer above the inversion.

5. SYNOPTIC SYSTEMS

5.1 Why Be Concerned About Synoptic Systems?

If, as stated above, many synoptic systems only enhance the local and diurnal weather patterns, why be concerned with synoptic systems at all? It is helpful to look back at the history of tropical meteorology to understand why they are important. In the 19th and early 20th centuries, tropical meteorology was mainly considered to be a climatology problem; i.e., the weather could be forecast if there was a long enough time series at a station to construct stable statistical parameters and their seasonal variations (Palmer 1951). A spectacular failure of climatology, however, was that it could not predict the development of tropical cyclones. Another problem was that climatology assumed that the steady trade winds occupied most of the oceanic regions, which was disproved by the observations taken during World War II. The wartime observations also showed that monsoon patterns were more complicated than could be predicted by climatology. This eventually lead to the development of the perturbation method of tropical forecasting in the 1940's and 1950's, which is the currently accepted tropical forecasting method. It states that the tropical atmosphere has a basic mean flow that is disturbed by perturbations developing in that flow. These perturbations have been shown to be primarily responsible for creating the environment that favors tropical rainfall. When composite tropical rainfall frequency versus amount curves are constructed, they consistently show that about 50% of total rainfall occurs during 10% of the recorded time interval (Ramage 1995). The lack of even one or two synoptic systems in a region often means that drought occurs (Riehl 1977).

There are other reasons to be concerned about synoptic systems. People acclimated to a tropical region can be affected by a drop in temperature of even 1°C (Riehl 1979). Excessive precipitation often leads to flash flooding and loss of life because soils in the Tropics tend to be shallow and the rivers cannot hold large amounts of runoff. Even though the chance of being affected by a tropical cyclone is rare in any one year, when it does occur the devastation can be nearly total. For example, in 1992 Hurricane Andrew caused an estimated $25 billion damage in the United States, most of it in south Florida, making it the costliest natural disaster in U.S. history (Mayfield et al. 1994). This section will describe synoptic models for tropical weather over oceanic regions and the Western Hemisphere.

5.2 Tropical Disturbances—"Easterly Waves" and Upper Cold (TUTT) Lows

The subject of "easterly waves" has had a complex history. It was summarized by Riehl (1954) as a model for the semi-periodic wind shifts and resulting disturbed weather that occur in the Caribbean region during the wet season. Components of his description of the wave, such as its cold core structure in the lower troposphere, maximum circulation near 700 mb, and cyclonic wind shift from northeasterly to southeasterly as the wave axis passed through a station, have been verified by later studies (Carlson 1969a, 1969b, Reed et al. 1977). Investigators have gotten different results from Riehl, however, about the vertical tilt of the wave axis and the location of the main convection and precipitation. The consensus seems to be that the wave usually tilts westward with height, as opposed to Riehl's description of eastward tilt, and that the major area of convection is ahead of the wave axis, rather than behind it (Carlson 1969a, 1969b, Reed and Recker 1971, Payne and McGarry 1977). Because later observations did not verify the complete model of the classical easterly wave, the National Hurricane Center (NHC) decided on the term "tropical wave" to describe "a trough, or cyclonic curvature maximum, in the trade wind easterlies [that] may reach maximum amplitude in the low or middle troposphere, or may be the reflection from the upper troposphere of a cold Low or equatorward extension of a mid-latitude trough" (Simpson et al. 1968). Over the North Atlantic Ocean they are also known as "African waves" because of their origin over the African continent (Pasch and Avila 1994).

Once the easterly wave model was published, tropical forecasters began using it to explain "any report of showers in the tradewinds" (Ramage 1995). This overuse led some to doubt the existence of easterly waves; for example, in 1966 J. C. Sadler gave a seminar titled "The Easterly Wave—the Biggest Hoax in Tropical Meteorology" at the National Center for Atmospheric Research (reported by Simpson et al. 1968). Although Reed and Recker (1971) detailed wave disturbances in the western Pacific, other researchers have claimed that the disturbances were just the surface reflections from upper cold (TUTT) lows (Carlson 1967, Erickson 1971, Sadler 1978, Kelley and Mock 1982).

Recent spectral studies by Shapiro (1986) and Lau and Lau (1990) suggested that tropical waves and upper cold lows are two parts of the same circulation. Shapiro (1986) argued that upper lows are displaced from their associated low-level troughs by a 60°-90° phase shift in the tropical North Atlantic. His Figure 15 is a time series from Grand Cayman showing that an upper trough preceded almost every low-level trough in July 1975. [It is interesting that Figure 1 from Avila and Pasch (1995) shows 200 mb trough axes preceding the low-level tropical wave axes being highlighted.] Lau and Lau (1990), using eight years of global analyses from the European Centre for Medium Range Weather Forecasting, identified four regions with tropical synoptic scale transients: the western Pacific, eastern Pacific, Bay of Bengal/northern India, and eastern Atlantic/western Africa. They showed that the transients had many of the same characteristics:

- westward tilt with height above 700 mb
- cold core upper troughs overlying the near-surface warm ridges
- near-surface troughs with a maximum cold core around 850 mb overlaid by a 300 mb warm core ridge
- a maximum of specific humidity ahead of or in the surface trough.

Major differences between the transients were the period, ranging from 3-5 days in western Africa to 6-9 days in the western Pacific and Indian regions, and the surface to 700 mb tilt, which could be eastward, westward, or vertical.

Taking the above studies into consideration, a model for tropical disturbances has been developed for this project. It combines parts of the easterly wave model with the upper cold low model. A synoptic-scale *tropical disturbance* is defined as a trough or cyclonic curvature maximum in the trade wind easterlies. Maximum circulation amplitude occurs around 700 mb and the coldest temperature occurs around 850 mb. The disturbance is usually paired with an upper cold low or trough that lies west of the 700 mb disturbance; its maximum circulation amplitude is around 200 mb and coldest temperature around 300 mb. The phase shift between the 200 mb and 700 mb circulations is about 180°, except for the western North Atlantic Ocean/Caribbean Sea region where the phase shift is between 60°-90°. No matter what the circulation phase shift is, the surface and 300 mb temperatures are usually about 180° out of phase. The surface weather ranges from intensification of diurnal cloudiness to a 24-36 hour rain event, depending on the strength of the system.

5.3 Shear Lines

5.3.1 Cold Fronts

Although mid-latitude meteorologists tend to drop cold fronts from maps after they pass a certain latitude, polar air does invade the Tropics, albeit in a modified form (Henry and Thompson 1976). During the low sun period, the subtropical highs move closer to the equator, allowing the mid-latitude troughs in the westerlies with their polar air to move further south. Cold fronts in the Tropics look more like shear lines because surface temperature and dew point differences across the front are usually small due to air mass modification as the polar air moves equatorward. But these shear lines have significant effects on tropical weather, being the primary source of precipitation during the dry season. Especially strong fronts have been known to penetrate deep into the Tropics and even cross the equator. Myers (1964) documented a Southern Hemisphere cold front that caused heavy rain in the Guyana Highlands of Venezuela (5°N) during July 1957.

In Central America, cold frontal passages happen frequently enough during the dry season that they have been given the name *northers* or *atemporalado* (Lessmann 1964, Ladd and Henry 1980). DiMego et al. (1976) and Horvath and Henry (1980) showed that frontal precursors in the central Caribbean region are a surface pressure minimum followed by a slow pressure rise several hours before frontal passage, accompanied by light precipitation and fog. After the shear line passes surface pressures rise rapidly, the wind direction shifts to a northerly quadrant and the wind speed increases, and continuous rain begins falling.

Brooks (1987) developed an index to forecast the arrival time of the *atemporalado* in Honduras based on the surface pressure difference between Merida, Mexico and Houston, Texas, Brownsville, Texas or Tampico, Mexico. Northers can also affect weather in the eastern Pacific Ocean. Strong Canadian cold air surges lead to cold air damming along the north-south oriented Rocky Mountains and ageostrophic northerly flow spilling into Mexico (Colle and Mass 1995). The flow continues to be dammed along the Sierra Madre Mountains until it reaches the Isthmus of Tehuantepec, where a gap in the mountains allows the cold air to move into the Pacific. The passage of cold air through the pass is accompanied by low temperatures, gusty winds, and squall lines characterized by rope clouds (Parmenter 1970, Bosart et al. 1995). The *Tehuantepecer*, as it is called, occurs an average of 20 times during the dry season and leads to a January climatological minimum in eastern Pacific sea surface temperature downstream from the Isthmus (Ramage 1995).

5.3.2 Surge of the Trades

Polar air also can also move into the Tropics during the high sun period. A mid-latitude migratory anticyclone can move southward until it reaches the subtropical high. It becomes caught in the circulation of the high and progresses southward and westward around it. As the anticyclone penetrates deeper into the Tropics, it loses all of its polar air characteristics and the leading edge of the anticyclone becomes a shear line (Walters et al. 1989). Because the shear line is embedded in the trade wind flow there are few warning signs of the line's approach. However, as the line passes through a station the weather changes quickly. The surface pressure rises rapidly, the temperature falls, the wind speed increases and showers and thunderstorms set in, with steady rain continuing for several hours to several days after the initial impulse. This phenomenon is called the *surge of the trades*. Surges have been linked to the development of tropical cyclones, monsoon depressions, squall lines, equatorial convection, and the onset of El Niño. Investigators believe that surges are caused by a sudden increase in the Hadley circulation but have not found the forcing mechanism that triggers them. They are notoriously difficult to forecast; as Ramage (1995) states, "[Surges] can seldom be anticipated."

5.4 Subtropical Lows

5.4.1 Subtropical Cyclones

Some areas in the Hawaiian Islands receive more than half their rainfall in the low sun months, usually considered to be the dry season. Hawaiians call these rains kona storms. In the first full study of the kona storms, Simpson (1952) named them *subtropical cyclones* and showed them to be a major circulation feature in the subtropics. The subtropical cyclone is a hybrid storm that has characteristics of both tropical and extratropical cyclones. Lawrence (1979), in a description of a January 1978 North Atlantic subtropical storm, detailed its characteristics:

Tropical

- significant convection close to the circulation center
- isolation from weather-producing systems in the westerlies

Extratropical

- an initial baroclinic energy source,
- sea surface temperatures at 24°C or colder
- maximum winds at a distance of 50 to 100 nautical miles from the storm center.

Ramage (1962) constructed a subtropical cyclone model that showed it to be a cold-core, direct circulation low with strongest winds between 600 mb and 400 mb and symmetrical distribution of precipitation in an annulus around the cyclone's center. Movement of the subtropical cyclone has been shown to be very erratic—it is as likely to move east as west, and some cyclones have been known to loop aimlessly over the oceans. Because it spends most of its life over water, it does not readily dissipate. The cyclone usually moves to a place where it is reabsorbed into the polar westerlies and loses all tropical characteristics.

Since 1970, NHC has identified and tracked subtropical cyclones with wind speeds at or above 18 m/sec in the North Atlantic. Data on these cyclones are published in *Monthly Weather Review's* annual Atlantic hurricane season report. Some interesting facts, a few contrary to the subtropical cyclone model, stand out. During the period 1970-1994, 55 subtropical cyclones were documented. Thirty-three of these storms subsequently developed into tropical cyclones. Two cyclones formed over land and moved out over water. Two other cyclones developed from dissipating tropical cyclones. These last two facts contradict the model that subtropical cyclones form over water and are of baroclinic origin (Frank 1975). Cyclones were documented for every month except February and March. Simpson (1952) stated that the greatest frequency of subtropical cyclone occurrence in the North Atlantic was November and January. NHC's data show that the maximum occurrence of subtropical cyclones was in August with 12 cyclones, followed by October with 11 and September with 8. Five November cyclones and one January cyclone were recorded during the same time period.

5.4.2 Temporales

The *temporale* is a type of subtropical cyclone that affects Central America. It has been described as an all-layer depression or as a hurricane without the winds or spiral banding. It usually occurs over the Pacific coast of Central America during the wet season, although some temporales also form along the Gulf of Honduras in December (Walters et al. 1989). The temporale is usually initiated by an initial area of instability caused by a stalled tropical depression or subtropical cyclone (Pacific side) or a cutoff low from a polar surge (Caribbean side). Monsoon trough surges or successive polar surges reinforce the moisture inflow into the circulation. Strong vertical shear develops between the low-level westerlies and upper-level trade wind flow from the Caribbean with the circulation center in the mid to upper troposphere. There is moderate to heavy rain but little to no convection in the temporale. Because the steering currents are usually light, the temporale may persist offshore for days, with the consequent risk of flooding in the region. It dissipates when it either moves onshore, cutting the storm off from its moisture source, or when warm air advection begins to move into the storm. Higher pressures in the subtropical ridge can push the temporale away from land and back into the Pacific (Gilford 1987).

5.5 Tropical Cyclones

Tropical cyclones are defined as "non-frontal, synoptic-scale cyclones developing over tropical or subtropical waters and having well-organized circulations. ... [They] form over all the tropical oceans except for the South Atlantic and the South Pacific east of about 130°W" (Ramage 1995). Tropical cyclones are warm-core direct thermal circulations with several distinct areas (Frank 1977):

- The *outer circulation* is where low-level cyclonic flow into the cyclone and upper-level anticyclonic flow away from the cyclone can first be detected. For a mature cyclone this may be at a distance of 14° (1550 km) away from the cyclone center.
- The *moat* is where the compensating downward motion to the intense upward motion in the cyclone occurs. The weather has been called "unusually and exceptionally fine" with prolonged suppression of convective activity.
- The *outer rainbands* mark the beginning of the cyclone proper. They are arranged in a spiral pattern with areas of showers and rain alternating with nearly clear areas.
- The *inner rainbands* are distinguished from the outer rainbands by the increased convection, stronger surface wind, and almost continuous rain.
- The *eyewall* is an annulus surrounding the center of the cyclone where the strongest winds, most vigorous convection, and heaviest rain occur.
- The *eye* is the center of the cyclone. It is marked by weak winds, very warm temperatures, and few clouds. The weather in the eye has been described as "sultry."

In the vertical, the most intense circulation is near the surface and decreases upward, with a weak anticyclone overlying the surface low beginning at about 200 mb. The types of hazards that can be encountered with tropical cyclones include very strong surface winds, heavy rain and associated flooding, tornadoes, and storm surges along coastal areas. Lightning is usually observed only in the outer rainbands and during cyclone decay (but see below).

The amount of precipitation with a tropical cyclone is highly variable and its distribution is asymmetric. In general, if the cyclone is moving between west and north, the heaviest rainfall will be in left rear quadrant of direction of motion; if the cyclone is moving northward, the heaviest rainfall will be in right front quadrant of direction of motion. Most regions of weak tropical cyclones (wind speeds less than 17 m/sec) have a diurnal cycle in rainfall rate, with the maximum rate in early morning and minimum rate in late afternoon (Rodgers and Pierce 1995). The inner-core regions (radius 111 km) of tropical cyclones with maximum sustained winds greater than 17 m/sec have a maximum rainfall rate in the evening. The greatest rainfall rates and most intense cyclones occur when sea surface temperatures are in the range of 27°C to 29°C.

Tropical cyclones are categorized by their maximum sustained near-surface wind speed. Systems with wind speeds less than 18 m/sec are tracked and watched for further development. Warnings are issued for tropical cyclones with wind speeds greater than 18 m/sec. The Saffir-Simpson scale is used to classify intense tropical cyclones, those with surface wind speeds greater than 32 m/sec (Landsea 1993):

Saffir-Simpson Category	*Maximum sustained wind speed (m/sec)*	*Minimum surface pressure (mb)*	*Potential damaging effects*
1	33-42	≥980	Minimal
2	43-49	979-965	Moderate
3	50-58	964-945	Extensive
4	59-69	944-920	Extreme
5	>69	<920	Catastrophic

These intense cyclones are called different names depending on their location:

- western North Pacific — typhoon
- Bay of Bengal and Arabian Sea — severe cyclone
- South Indian and South Pacific — tropical cyclone
- North Atlantic and eastern North Pacific — hurricane.

The record low pressure for a tropical cyclone, 870 mb, was recorded in Typhoon Tip on 12 October 1979 near 17°N 138°E (Dunnavan and Diercks 1980). The North Atlantic basin record of 888 mb was set by Hurricane Gilbert in 1988 near the Yucatan Peninsula (Willoughby et al. 1989.)

Investigators have identified six conditions necessary (but not sufficient) for formation of a tropical cyclone (Riehl 1979):

- The sea surface temperature must be at or greater than 26°C.
- Location must be poleward of the equatorial belt 5°N-5°S (although at least one tropical cyclone has been documented as forming in the equatorial belt; see Holliday and Thompson 1986).
- There must be weak vertical wind shear, usually defined as less than 10 m/sec.
- A mechanism for upper-level outflow near the forming cyclone must be present.
- There must be a preexisting surface disturbance.
- The atmosphere must be capable of permitting deep convection to occur.

These conditions are most often met in the western North Pacific, where intense tropical cyclones can occur at any time of year. In the other locations, tropical cyclones are wet season phenomena.

What triggers the formation of a tropical cyclone continues to be the subject of much debate. The "preexisting surface disturbance" includes tropical waves, subtropical lows, surface reflections of upper cold lows, disturbances in the ITCZ (both kinds), and even extratropical cyclones. Landsea (1993) calculated that 83% of Saffir-Simpson category 3-5 hurricanes originated as tropical waves. Frank and Clark (1980) first suggested that some eastern North Pacific cyclones have their initial development in the western Caribbean; NHC continues to monitor the number of tropical waves that cross Central America and subsequently become tropical cyclones (for example, see Avila and Pasch 1995). The general formation process is the same in every cyclone basin; a cold-core, energy-importing disturbance gradually transforms into a warm-core, energy-exporting cyclone.

How and why a tropical cyclone intensifies is also not fully understood. Sadler (1976, 1978) showed that the North Pacific TUTT was a major influence on the intensity of typhoons. Recent studies by Venne et al. (1989), Lyons and Keen (1994) and Molinari et al. (1994) suggest that lightning in the eyewall, which is usually non-electrical, is an indicator that the cyclone is entering a period of intensification. Willoughby and Black (1996) reported that part of the reason for Hurricane Andrew's intensity at landfall was that it was in the process of deepening after a second eyewall replaced the original eyewall.

Tropical cyclones are difficult to forecast with data from a single station only. Steep pressure falls only begin about 12 hours ahead of the cyclone center, temperatures rise significantly only in the eye, and storm surges often strike with no warning, such as on Galveston Island in 1900. Single-station tropical forecasters can predict tropical cyclones if they are observant. When surface wind speeds are 25% or more above normal, the flow curves cyclonically with time, and the wind direction is from a quadrant different from the normal flow, a cyclone should be expected. The arrival of long sea swells with a wave frequency of 2-4 per minute (average wave frequency is 10-15 per minute) begins when the cyclone is 800 to 1600 km away. The direction from which the swell approaches indicates the direction the cyclone will take (see section 8.4.6). Abnormally high tides, particularly along the shore lines of partially enclosed bodies of water, indicate the presence of a cyclone in the vicinity. In the moat region, normal convective activity is suppressed. Cirrus can be observed to radiate from a point on the horizon in the general direction of the cyclone. If one is available, microseismographs can distinguish between tropical cyclone vibrations, which have a period of 2-6 sec, and regular wave vibrations. Although tropical cyclones are rare at any particular station, those stations in tropical cyclone basins need to monitor cyclone warning signs during the wet season.

6. AREAS FOR FURTHER INVESTIGATION

This report has detailed the large-scale circulation features of the Tropics, the local controls that dominate the weather, and some of the synoptic systems that can affect tropical stations. There remain several areas in the Tropics that need to be investigated in order to make this forecasting system one that can be used in all areas of the Tropics:

- SWANEA (Southwest Asia-Northeast Africa) region—This region is important strategically because of its large oil reserves. Meteorologically speaking, it is the location of the western branch of the Asian monsoon circulation. Coastal upwelling, dust storms, seasonal jet streams, mountains and irregular coastlines contribute in making this region one of Trewartha's (1961) "problem climates." The SWANEA climatological studies (Vojtesak et al. 1990, Vojtesak et al. 1992, Walters et al. 1991, Vojtesak et al. 1991) will be extensively examined.

- South and East Asia—In this region are developing countries that are growing economically. The weather is dominated by the Asian monsoon circulation. The synoptic systems that affect this region, such as typhoons and monsoon depressions, have caused great loss of life because of the population density and poor communications. The main resources to be studied will be Ramage (1971) and Asnani (1993).

- Central Africa—The western part of this region is the primary genesis area for synoptic systems, such as tropical waves and squall lines, that affect the Western Hemisphere Tropics. It has a monsoon circulation and is affected by the Sahara Desert, coastal upwelling , seasonal jet streams, dust storms, mountains, and two tropical oceans. The Equatorial Africa climatological study (Donahue et al. 1995) will be the main resource consulted.

- Southern Hemisphere—Little attention in this report has been paid to the Southern Hemisphere. However, most of its land masses lie in the Tropics. It experiences more polar surges than the Northern Hemisphere because of the Antarctic continent and relatively few mountains to hinder polar air movement. The South America (Gilford et al. 1992) and Southern Africa (Traxler et al. 1994) climatological studies will be the main references, supplemented by other resources.

This report has shown that tropical weather can be forecast with more than a persistence-climatology approach. Single-station forecasters will be able to prepare a forecast with the use of the tropical expert system, which will have the knowledge base to alert them when a synoptic system is suspected by examining subtle changes in the meteorological parameters.

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8. APPENDIX—TROPICAL WEATHER CHARACTERISTICS

TABLE OF CONTENTS

8.1. Characteristics of Station

8.1.1. Geography

1. Is station in the tropics—30°N-30°S?
2. Is station on a continent or on an island?
3. Is station windward or leeward of mean flow?
4. Is station on or near an ocean/lake coastline?
5. Is terrain around station over 300 m (1000 ft)?
6. What is the character of the vegetation cover around station—dry & barren, moist & lush, etc.?

8.1.2. Climatological, Seasonal, Synoptic, and Local Controls

1. What is the climatological regime of station?
   a. Rainforest: Year-round rainy season; annual precipitation greater than 100 in.
   b. Monsoon: Heavy rainy season and short dry season.
   c. Savanna: Short but heavy rainy season and long dry season.
   d. Steppe: Long dry season and short rainy season.
   e. Desert: Year-round dry season; annual precipitation less than 10 in.
2. From section 8.2, what are the seasonal circulations that are expected to affect station?
3. From section 8.3, what are the local features that are expected to affect station?
4. From section 8.4, what are the synoptic systems that are expected to affect station?
5. From section 8.5, what kinds of obstructions to visibility are expected to regularly affect station?

8.1.3. Climatology

1. Determine seasonal values of
   a. wind roses
   b. upper-air sounding
   c. SST if near ocean
2. Determine monthly values of
   a. mean and record maximum and minimum temperatures
   b. record maximum, record minimum, and mean precipitation amounts
   c. days with rain and thunderstorms
   d. mean surface pressure
   e. percent cloudiness and relative humidity
   f. height of trade wind inversion
3. Determine monthly percent frequency of
   a. ceilings
   b. visibilities
   c. rainfall and thunderstorms
   d. fog

4. Determine mean hourly surface values by season of
   a. pressure
   b. temperature
   c. dew point temperature
   d. gradient wind
5. Determine hourly percent frequency by season of
   a. ceilings
   b. visibility
   c. rainfall and thunderstorms
   d. fog

8.2. Climatological Features

8.2.1. Intertropical Convergence Zone (ITCZ)

1. Type, location, and time of year
   a. <u>Monsoon trough</u> [easterlies on poleward side, westerlies on equatorward side]
      i. eastern North Pacific Ocean & Central America, May-Nov
      ii. Caribbean South America, May-Nov
      iii. central South America, Nov-Mar
      iv. South and Southeast Asia, May-Oct
      v. Indonesia & Malaysia, Apr-Jun & Nov-Dec
      vi. northern Australia and South Pacific Ocean, Dec-Mar
      vii. northern & western Africa and eastern North Atlantic Ocean, Apr-Sep
      viii. southern Africa & Madagascar, Dec-Mar
   b. <u>Near-equatorial trade wind convergence</u> (NETWC) [northeasterlies on north side, southeasterlies on south side]
      i. western Africa, North Atlantic Ocean & northeastern South America, Oct-Mar.
      ii. central & western North Atlantic Ocean, Apr-Sep.
      iii. northwestern South America & eastern North Pacific Ocean, Nov-Apr.
      iv. central & western North Pacific Ocean, Jan-Dec.
      v. South Indian Ocean, Nov-Mar.
2. Features in and around wind confluence zone
   a. <u>Trade wind inversion</u>: Poleward of zone, inversion is well marked between 900-800 mb. As zone is approached, inversion begins to rise and is destroyed in zone through 200 km equatorward of zone. About 300-400 km equatorward of zone, weaker inversion is established between 800-700 mb.
   b. <u>Winds</u>
      i. *Monsoon trough*: Vertical wind profile equatorward of zone is low-level westerlies (sfc-850 mb) and mid- to upper-level easterlies (above 700 mb). Note that the westerlies may only begin 1000-2000 ft above a shallow sfc layer of easterlies. Vertical wind profile poleward of zone is deep easterlies (sfc-tropopause).

ii. *NETWC*: Vertical wind profile on either side of zone is deep easterlies (sfc-tropopause).

c. Pressure: Sfc pressure is below 1012 mb in zone.

d. Clouds

i. *Monsoon trough*: In zone, widely sct Cu. In convection 100-200 km equatorward of zone, parallel bands of Cb and Cu with comparatively clear spaces in between; extensive sheet of As and broad deck of Cs above convection. Cloud heights can reach over 40,000 ft.

ii. *NETWC*: Cu, Sc, and Ac with few Cb in zone. Cloud heights average 10,000-15,000 ft.

e. Temperatures: Vertical temperature structure is cold-core around 700 mb and warm-core above 400 mb in zone. SST's are at max in zone.

f. Relative humidity: Vertical moisture profile has max in region of max convection.

g. Weather

i. *Monsoon trough*: Showers and T-storms occur 100-200 km equatorward of zone.

ii. *NETWC*: Showers and few T-storms occur in zone.

3. Notes

a. Many tropical cyclones develop from synoptic disturbances in the ITCZ.

b. At the equator, convection in the ITCZ tends to be suppressed at all areas of the globe except for Africa.

8.2.2. Tropical Upper-Tropospheric Trough (TUTT)

1. Season: high sun

2. Location

a. North Atlantic Ocean (mean Aug. position 35°N 30°W to 30°N 45°W to 25°N 65°W to Haiti to Yucatan Peninsula).

b. North Pacific Ocean (mean Aug. position 35°N 145°W to 30°N 160°W to 25° N 180° to 22° 135° E).

c. South Atlantic Ocean (mean Feb. position near E coast of Brazil).

d. South Pacific Ocean (mean Feb. position 5°S 165°W to 10°S 150°W to 15°S 135°W).

2. Features in and around the trough

a. Winds: Wind direction shifts cyclonically from NNE to WSW (NH) in a narrow zone at 200 mb.

b. Pressure: Little to no change at sfc. Heights above 700 mb show a negative anomaly.

c. Clouds: Little to no clouds in trough. Major cloud systems are south of the trough line.

d. Temperatures: Temps above 700 mb show a negative anomaly with max anomaly at 300 mb.

e. Relative humidity: Vertical moisture profile is dry in trough.

f. Weather: Little to no wx associated in trough.

3. Notes
   a. Although the trough itself has little weather, the lows that develop in the TUTT are associated with tropical disturbances (see section 8.4.1).
   b. TUTT lows are a source for tropical cyclones developing north of 20°N.

8.3. Local Circulations

8.3.1. Blocking by Terrain

Local circulations can develop in spite of gradient wind speeds that would ordinarily disrupt them. The gradient wind can be forced to go around the terrain rather than over it, a phenomenon known as "blocking." Flow stagnation occurs on the windward and leeward sides of the terrain, resulting in lower than expected wind speeds at the surface, and allowing local circulations to develop there. [Note that the wind speeds on the sides of the terrain perpendicular to the windward and leeward sides are often higher than the gradient wind speed because the diverted flow is accelerated as it passes around the terrain.] Blocking can be predicted by calculating the Froude number:

$$Fr \equiv \frac{U}{hN} \tag{1}$$

where

U = gradient wind speed unaffected by terrain (m/sec)
h = height of terrain (m)
N = Brunt-Väisälä frequency (sec^{-1})

$$\equiv \left[\frac{g}{T}(\Gamma_d - \Gamma)\right]^{1/2} \tag{2}$$

where

g = gravitational acceleration = 9.8 m/sec^2
T = temperature at gradient level (K)
Γ_d = dry adiabatic lapse rate = 0.0098 deg/m
Γ = lapse rate from surface to base of inversion (deg/m)

The critical values of the Froude number are (Smolarkiewicz and Rotunno 1989, Lin and Wang 1996):

Froude number	*Effect on flow*
>1.0	no upstream blocking; stationary mountain waves.
0.5-1.0	upstream blocking on windward side; strong downslope winds on lee side.
0.1-0.5	upstream blocking with flow stagnation on windward and leeward sides.
<0.1	negligible gradient wind; thermal forcing is dominant.

Thermal forcing can affect upstream blocking in low Froude number regimes ($Fr<1.0$). The magnitude of the trajectory-integrated thermal forcing, η^*, is defined as (Reisner and Smolarkiewicz 1994):

$$\eta^* \equiv \frac{L^* Q_0}{Uh\Gamma} \tag{3}$$

where

L^*	=	characteristic horizontal length scale of thermal forcing (m) (For an island, L* = island radius)
Q_0	=	climatological heating rate (deg/sec)
U	=	gradient wind speed unaffected by terrain (m/sec)
h	=	height of terrain (m)
Γ	=	lapse rate from surface to base of inversion (deg/m).

A combination of η^* and Fr,

$$2\eta^* + \tfrac{4}{3}Fr, \tag{4}$$

forecasts whether thermal forcing will dominate terrain forcing. When $2\eta^* + \frac{4}{3}Fr < 1$, the upwind flow will always exhibit upstream stagnation during the heating cycle and the flow will always be blocked. When $2\eta^* + \frac{4}{3}Fr > 1$, there will be a critical transition during the daytime heating cycle from a blocked to an unblocked flow regime. Note that for $\eta^* \geq 1$ the flow will be unblocked regardless of the value of Fr; for $|\eta^*| << 1$ the effects of thermal forcing are negligible. Also note that the larger the value of η^* is, the stronger the lee flow response will be, because the lee flow is dominated by thermal forcing.

8.3.2. Sea (Lake, River) Breeze

1. Necessary factors for development
   a. Land area must be large enough to generate a deep local circulation; for example, island width must be greater than 100 km in order to generate a significant sea breeze. If near a lake, the lake must be large enough to affect local circulations.
   b. Station must be within 200 km of coastline.
   c. Time must be during daylight hours.
   d. Land temperature must be greater than sea surface temperature.
   e. Gradient wind speed must be less than 6 m/sec.
   f. Atmosphere must be unstable in vertical.
   g. Cloudiness must be less than 50% of total sky. Bkn to ovc low clouds or ovc Ci will prevent the formation of a superadiabatic layer near the sfc.
2. Factors that enhance development and inland penetration
   a. Dry barren ground, because it heats up more rapidly than moist vegetative ground. (Note: In Australia, the sea breeze front has been observed to penetrate almost 300 km inland in a hot desert region.)
   b. Windward coast without mountains high enough to penetrate the trade wind inversion, because the terrain does not disturb the gradient flow.
   c. Leeward coast with mountains high enough to penetrate the trade wind inversion, because the terrain diverts and thus weakens the offshore flow.
   d. Location close to equator (approximately 5°N-5°S), because sea breeze will not veer (NH) with time due to near-zero Coriolis force so inland penetration is greatest.

3. Effect of gradient wind
   a. Offshore flow: The sea breeze convergence zone is strong because of the horizontal forcing that leads to strong upward vertical motion. The convergence zone develops relatively late in the day and does not move far inland because of the opposing large-scale wind. A late-afternoon sea breeze onset can look like a cold FROPA. Strongest showers and T-storms occur with this wind regime. Gradient wind greater than 6 m/sec will keep the convergence zone offshore.
   b. Onshore flow: The sea breeze convergence zone is weaker than the convergence zone due to offshore flow, but the zone develops earlier and penetrates further inland than the offshore flow zone. Gradient wind greater than 4 m/sec will prevent the sea breeze from developing.
   c. Parallel flow with high pressure over land: The sea breeze acts like the case of offshore flow because friction induces an offshore wind component.
   d. Parallel flow with low pressure over land: The sea breeze acts like the case of onshore flow because friction induces an onshore wind component.
4. Sea breeze forecasting index (Walsh 1974)
   In order to predict whether an offshore gradient wind U will prevent a sea breeze from moving onshore, need to calculate the minimum temperature difference $\Delta T_{\min}$) between land and sea needed to initiate the sea breeze:

$$\Delta T_{\min} = \frac{T_0}{0.11g}\left(\frac{\omega}{\kappa}\right)^{1/2} U^2 \qquad (5)$$

   where

$\Delta T_{\min}$	=	temperature$_{\text{land}}$ - SST
T_0	=	temperature (K) of land unaffected by water mass at initial time (usually the temp at 0600-0800 LST)
g	=	gravitational acceleration = 9.8 m sec^{-2}
ω	=	angular velocity of earth = 7.292×10^{-5} rad sec^{-1}
κ	=	eddy diffusion coefficient = 10 m^2 sec^{-1}
U	=	gradient wind speed (m sec^{-1}).

   When the predicted difference between max land temp and SST is greater than $\Delta T_{\min}$, the sea breeze will move onshore. Note that this index will not work for predicting the sea breeze on smaller islands because of the requirement that T_0 be unaffected by the water mass.
5. Details of sea breeze convergence zone
   a. Sea breeze convergence zone has passed station when wind shifts to onshore or onshore gradient wind strengthens by 1-2 m/sec, air temperature falls, and relative humidity rises. Offshore stratus or fog may be carried in by sea breeze.
   b. Sea breeze reaches maximum intensity around the time of greatest temperature difference between land (unaffected by sea breeze) and sea.
   c. A line of scattered cumulus oriented somewhat parallel to the coastline indicates the position of the sea breeze convergence zone. Showers and/or T-storms may be expected along this line beginning around the time of maximum intensity.

8.3.3. Land Breeze

1. Necessary factors for development
   a. Region must capable of developing a sea breeze circulation.
   b. Station must be within 200 km of coastline.
   c. Time must be during nighttime hours.
   d. Land temperature must be less than sea surface temperature.
   e. Gradient wind must be less than 6 m/sec.
   f. The atmosphere must be stable in vertical.
   g. Cloudiness must be less than 50% of total sky. Bkn to ovc low clouds or ovc Ci will hinder radiation cooling at the sfc.
2. Factors that enhance development and offshore penetration
   a. Dry barren ground, because it cools down more rapidly than moist vegetative ground.
   b. Leeward coast without mountains high enough to penetrate the trade wind inversion, because the terrain does not disturb the gradient flow.
   c. Windward coast with mountains high enough to penetrate the trade wind inversion.
   d. Offshore gradient wind, because it reinforces the weak offshore flow of the land breeze.
   e. Location away from equator (approximately 5°N-5°S), because of the small land/sea temperature gradients near the equator and because there is no rotation of the sea breeze circulation due to the near-zero Coriolis force.
   f. Strong surface heating during the day, because the initial flow of the land breeze is dependent on the daytime surface heating, not nighttime surface cooling.
3. Effect of gradient wind
   a. <u>Onshore flow</u>: The land breeze convergence zone is weak and shallow in vertical. The convergence zone may not move offshore because of the opposing large-scale wind. Onset time is usually a few hours after midnight LST. Gradient wind greater than 5 m/sec onshore will prevent the land breeze from developing.
   b. <u>Offshore flow</u>: The land breeze convergence zone is relatively strong and deep, and moves offshore quickly. Onset time is usually between sunset and midnight LST. Gradient wind greater than 6 m/sec offshore will overwhelm the land breeze.
   c. <u>Parallel flow with high pressure over land</u>: The land breeze acts like the case of offshore flow because friction induces an offshore wind component. Onset time is around midnight LST.
   d. <u>Parallel flow with low pressure over land</u>: The land breeze acts like the case of onshore flow because friction induces an onshore wind component. Onset time is around midnight LST.
4. Details of land breeze convergence zone
   a. Onset of land breeze has occurred when nearly calm wind shifts to 1-2 m/sec offshore or offshore gradient wind strengthens slightly, air temperature rises, and relative humidity decreases.

b. A line of scattered cumulus oriented somewhat parallel to the coastline indicates the position of the land breeze convergence zone. Showers and/or T-storms may be expected along this line near sunrise.
c. Equatorward of 30° the land breeze will persist for some time after sunrise. Poleward of 30° the maximum land breeze will occur some time before sunrise. Around 30° the maximum land breeze will occur at sunrise; the land breeze circulation is strongest at this latitude.

8.3.4. Anabatic (Upslope) Flow

1. Necessary factors for development
   a. Terrain must be greater than 1,000 ft (300 m) above sea level.
   b. Time must be during daylight hours.
   c. Weather must be clear to partly cloudy (less than 50% cloud cover).
   d. Gradient wind must be less than 6 m/sec. [Gradient winds greater than 6 m/sec overwhelm anabatic flow regardless of wind direction.]
2. Mountain regions where anabatic flow is enhanced
   a. Windward slope because gradient wind is forced up the terrain.
   b. Equatorward-facing slope because of greater insolation.
3. Indications that anabatic flow has developed
   a. Mountain slope station reports wind direction to be uphill. Valley station reports wind direction to be upvalley.
   b. Cumulus forms over mountain tops and along ridges.

8.3.5. Katabatic (Downslope) Flow

1. Necessary factors for development
   a. Terrain must be greater than 1,000 ft (300 m) above sea level.
   b. Time must be during nighttime hours.
   c. Skies must either be clear, or cloudy and rainy with nearly saturated air.
   d. Gradient wind must be less than 6 m/sec. [Gradient winds greater than 6 m/sec overwhelm katabatic flow regardless of wind direction.]
2. Regions where katabatic flow is enhanced
   a. Leeward slope because of the absence of the gradient wind. (Windward slopes have weak to nonexistent katabatic flow except when $Fr < 0.1$.)
   b. Poleward-facing slope because of lesser insolation during the day.
   c. Slopes with extensive cloudiness and precipitation because precip evaporation makes the air layer next to the slope neutral to negatively buoyant.
3. Indications that katabatic flow has developed
   a. Mountain station reports wind direction to be downhill. Valley station reports wind direction to be downvalley.
   b. Fog and low stratus forms over valley, indicating presence of inversion.

8.3.6. Interaction of Local Circulations with Gradient Wind

1. Sea breeze and anabatic flow
   a. <u>Windward side</u>: Sea breeze, anabatic flow and gradient wind reinforce one another.

b. Leeward side: Sea breeze-anabatic flow weak because of opposing gradient wind; circulation may not reach top of mountain

2. Land breeze and katabatic flow
   a. Windward side: Land breeze and katabatic flow weak because of opposing gradient wind; circulation may not reach coastline.
   b. Leeward side: Land breeze, katabatic flow, and gradient wind reinforce one other.

8.3.7. The Tropical Rainstorm

1. Time and location
   a. Afternoon to early evening
      i. continental areas with clear skies in morning and sufficient moisture (radiative heating)
      ii. islands and regions of elevated terrain
      iii. windward sides of mountains
      iv. leeward sides of large islands and peninsulas
      v. oceanic ITCZ's and the South Pacific Convergence Zone.
   b. Night to early morning
      i. continental areas with cloudy skies in evening and sufficient moisture (radiative cooling)
      ii. areas with low-level nocturnal jet
      iii. windward sides of large islands and peninsulas
      iv. valleys where mountain winds are blowing in opposite direction to gradient wind
      v. coastal areas
      vi. wet monsoon regions
      vii. open ocean regions away from the ITCZ.
2. Meteorological parameters
   a. Trade wind inversion: When the trade wind inversion is present with a corresponding dry layer, deep convection is more likely if there is a moist layer (mixing ratio increases about 2 g/kg) above the dry layer. A deep dry layer associated with the inversion will limit convection to below the inversion base.
   b. Clouds: Cb cloud height must extend above 30,000 ft for a thunderstorm to form. The lifetime of an individual Cb is about 2 hours. A Cb is typically 1-10 NM wide.
   c. Pressure: 24-hr sfc pressure tendency falls for some hours ahead of a rain event. It begins to rise weakly 30-60 minutes ahead of main precip and then rises rapidly by about 2 mb as cold air mass arrives.
   d. Winds: Vertical wind shear should be weak. In order for convection to persist, anticyclonic outflow must be present in the high (~200 mb) troposphere.
   e. Stability: Atmosphere must be convectively unstable.
   f. Temperature: After moderate to heavy precipitation, the boundary layer cools by about 1°C and is drier by about 1 g/kg.

g. Weather: Precipitation is in the form of rain showers. Precip duration is on the order of an hour. The core of an avg rainstorm produces at least 25 mm of rain.

3. Notes
   a. The diurnal cycle of rainfall is most evident with intense deep convection and synoptic-scale systems. Light rain does not have a diurnal cycle.
   b. Conditions that inhibit daytime convection: early morning cloudiness in the form of fog, St, Ci shield; rain within the previous 12 hours.
   c. In general, only one shower/T-storm occurs over a station on any given day. The growth of new convection is limited until the boundary layer has recovered to its fair weather state.

8.4. Synoptic Systems

8.4.1. Tropical Disturbances—"Easterly Waves" and Upper Cold Lows

1. Season, location, and period
   a. wet; western Africa/North Atlantic Ocean, Caribbean Sea; 3-5 days.
   b. wet; eastern North Pacific Ocean; 5-6 days.
   c. wet; western North Pacific Ocean, Bay of Bengal/northern India; 6-9 days.
2. Disturbance cycle
   a. 700 mb ridge/200 mb low/trough
      i. *Winds*: Meridional component of wind switches from south to north in sfc-500 mb layer as ridge axis passes; meridional component of wind switches from north to south in 300-100 mb layer as trough passes. Wind speeds are light but begin to increase towards end of period.
      ii. *Pressure*: 24-hr sfc pressure tendencies show slight rise. 200 mb geopotential heights reach minimum.
      iii. *Clouds*: Sct trade Cu. If the low circulation extends below 700 mb, will also have sct Sc and Cb. Late in period begin to see towering Cu/Cb with sct Ac and Ci.
      iv. *Temperatures*: Sfc temps rise between 0.5°-1°C after sfc ridge passes through. Above 500 mb temperatures fall at least 1°C after low/trough passes. Note that the strongest lows may have temperature anomalies of up to 4°-5°C below average at 300 mb.
      v. *Relative humidity*: Vertical moisture profile is dry at all levels, typical of an area not recently subjected to organized convection.
      vi. *Precipitation*: Convection is usually suppressed in the vicinity of an upper cold low. If the low circulation extends below 700 mb, will have sct showers. Precipitation amount is roughly 50% of average diurnal rainfall.

b. <u>700 mb max N wind/200 mb max S wind</u>
   i. *Winds*: Sfc-400 mb layer has winds with northerly meridional component. In layer 300-150 mb have winds with southerly meridional component. Meridional wind speed components at all levels reach their maximum value.
   ii. *Pressure*: Sfc pressure begins to fall at rate of 1-2 mb/24 hr. At 200 mb, geopotential heights begin to rise as cold low/trough moves westward.
   iii. *Clouds*: Bkn to ovc Ac and Cs. Sc, Cb and Cs in areas of precipitation.
   iv. *Temperatures*: Sfc temps show little change. Upper level temps begin to warm.
   v. *Relative humidity*: Vertical moisture profile begins to increase in sfc-400 mb layer.
   vi. *Precipitation*: Lgt-mdt showers and occnl T-storms; lgt rain between showers. Precip amount is roughly 150% of average diurnal rainfall.

c. <u>700 mb trough/200 mb ridge</u>
   i. *Winds*: Meridional component of wind switches from north to south in sfc-500 mb layer as trough passes; meridional component of wind switches from south to north in 300-100 mb layer as upper ridge axis passes. Wind speeds in near-sfc layer increase to 20-25 kts with higher gusts in showers/T-storms.
   ii. *Pressure*: Sfc pressure reaches minimum with passage of wind shift line and then begins to rise. 200 mb geopotential heights reach maximum.
   iii. *Clouds*: Bkn to ovc Ac and Cs. Sc, Cb and Cs in areas of precipitation.
   iv. *Temperatures*: Sfc-500 mb temps reach minimum several hours after wind shift has passed station. Temps in 300-100 mb layer warm about 1° C after passage of upper ridge axis.
   v. *Relative humidity*: Vertical moisture profile reaches max behind sfc wind shift line.
   vi. *Precipitation*: Showers and occnl T-storms are associated with sfc wind shift line. Note that equatorial westerlies near the surface *always* have precip associated with them, even if the westerlies are only temporary and associated with a synoptic situation. Precip amount is roughly 100-125% of average diurnal rainfall.

d. <u>700 mb max S winds/200 mb max N wind</u>
   i. *Winds*: Sfc-400 mb layer has winds with southerly meridional component. In layer 300-150 mb have winds with northerly meridional component. Meridional wind speed components at all levels reach their maximum value.
   ii. *Pressure*: Sfc pressure rises weakly. 200 mb geopotential heights begin to fall.
   iii. *Clouds*: Sct Cu with some Ci. Sct to bkn Cb in association with 200 mb wind speed max.
   iv. *Temperatures*: Sfc temps show little change. Upper level temps begin to cool.
   v. *Relative humidity*: Vertical moisture profile begins to decrease.

vi. *Precipitation*: Convection is mostly suppressed on west side of upper low except for sct showers in association with 200 mb northerly wind max. Precip amount is 50-75% of average diurnal rainfall.

4. Notes on upper cold lows
   a. The center of the cold low is relatively cloud- and wx-free because it is a direct circulation, with cold air sinking in the center of the low and warm air rising in the periphery of the low. About 60% of cold lows do not reach 700 mb and thus have little effect on the surface wx directly beneath them. The lower the low circulation penetrates towards the surface, the stronger the 200 mb circulation and the more cloudiness associated with it.
   b. Cold lows that move over large land areas show a distinct diurnal variation in convection, with the strongest convection occurring in phase with the normal diurnal heating cycle (i.e. showers/T-storms reach a peak in the late afternoon and early evening).
5. Notes on "easterly waves"
   a. The area of maximum precipitation enhancement depends on the tilt of the "wave" in the sfc-700 mb layer:
      i. *"Wave" tilting westward with height*: Max precip occurs ahead of sfc wind shift line.
      ii. *"Wave" tilting eastward with height*: Max precip occurs to rear of sfc wind shift line.
      iii. *"Wave" with no vertical tilt*: Max precip occurs along the sfc wind shift line.
      iv. *"Wave" in the ITCZ*: Max precip occurs on the equatorward side of the ITCZ and ahead of sfc wind shift line, regardless of tilt.
   b. Strongest "wave" intensities occur with a low-level westerly wind layer about 100-150 mb thick in the lower troposphere, found either in the ITCZ or temporarily in the trade wind flow due to local circulation around the disturbance.
   c. When strong upper westerlies intrude into the tropics (strong vertical shear), both upper cold lows and "easterly waves" will be damped or non-existent.
   d. The National Hurricane Center calls "easterly waves" in the North Atlantic Ocean "tropical waves" and defines three areas of origin:
      i. West Africa
      ii. upper cold low in the North Atlantic TUTT
      iii. equatorward extension of a mid-latitude trough.

8.4.2. Cold Fronts

1. Season & location: wet-to-dry transition, dry, and dry-to-wet transition; tropical continents and adjoining oceans.
2. Ahead of front (beginning 24-48 hrs before FROPA):
   a. <u>Trade wind inversion</u>: Inversion begins to weaken and rise as atmosphere becomes more unstable.

b. Winds: SE winds at near-sfc levels. In vertical, base of polar westerlies lowers; westerlies have a southerly meridional component. Note that the upper trough may precede the sfc front; if the base of the westerlies lowers and direction switches from southerly to northerly, expect a sfc front.
c. Pressures: Sfc pressures poleward of 20° fall steadily; equatorward of 20° sfc pressures first fall and then begin slow rise. 24-hr pressure falls rarely exceed 5 mb.
d. Clouds: Clouds are widely sct Cu and some Ci, gradual increase to bkn Cu congestus and ovc As and Cs.
e. Temperatures: Temps increase slightly or remain steady; dew point temps rise; temp of 1000-700 mb layer increases. In upper troposphere, temps begin to cool and upper thermal gradient begins to increase.
f. Weather: Wx is haze and/or fog, possible drizzle or rain.

3. In frontal zone (FROPA to 24 hrs after FROPA)
   a. Trade wind inversion: Inversion is destroyed.
   b. Winds: Sfc winds abruptly shift to N-NW and speed increases with gusts 20-35 kts for period 12-24 hrs after wind shift; higher elevations may see wind gusts up to 80 kts; upper-level winds shift from southerly to northerly meridional component as upper trough passes through station. Base of the polar westerlies falls to its lowest height.
   c. Pressure: Sfc pressures poleward of 20° reach minimum and begin to rise, sfc pressures equatorward of 20° rise more rapidly.
   d. Clouds: Cloud structure changes from Cu to St-Sc. Cloud bases lower after FROPA, especially in first 3 hrs after intrusion of cold air.
   e. Temperatures: Dew point temps begin fall as soon as wind shift occurs; sfc temps may not begin to fall until several hours after wind shift; 850 mb temp best for determining if FROPA has occurred. Upper thermal gradient reaches max.
   f. Weather: Wx is continuous lgt rain with periods of mdt-hvy rain/rain showers, possible T-storm.
4. Behind front (24-48 hrs after FROPA):
   a. Trade wind inversion: Inversion becomes reestablished.
   b. Winds: Wind speeds at all levels return to climatological normals. Meridional wind components at all levels decrease. Base of the polar westerlies rises.
   c. Pressures: Sfc pressures return to climatological normals.
   d. Clouds: Clouds are ovc Sc with some Cb, As and Cs above; breaking up to sct Cu after precip ends.
   e. Temperatures: Sfc temps and dew point temps reach minimum and then begin to rise; temp of 1000-700 mb layer decreases. Upper thermal gradient lessens.
   f. Weather: Wx is rain/rain showers, possible T-storm, for 1-3 days after FROPA; precip amounts will be enhanced over E-W oriented mountains because of orographic lifting.

5. Forecasting techniques if have additional data
    a. Central America: Sfc pressure difference of 15-19 mb between Houston, TX, Brownsville, TX, or Tampico, Mexico, and Merida, Mexico means that polar surge can be expected in about 24 hrs in central Honduras. Surge will become quasi-stationary on Honduras-Nicaragua border and dissipate within 48-72 hrs. Sfc pressure difference greater than 19 mb means that polar surge will move through Central America and become quasi-stationary in eastern Panama.
    b. Southeast Asia/South China Sea: Sfc pressure difference greater than 10 mb between 30°N 115°E (near Wuhan, China) and Hong Kong means that NE monsoon cold surge can be expected in about 24 hrs over coastal Vietnam and northern South China Sea, with sfc winds exceeding 20 kts.
6. Notes
    a. Cold air is funneled through the mountain passes of southern Mexico (resulting winds are called "Tehuantepecer"), Nicaragua, and Panama. Downstream in the Pacific, January climatology shows high winds, cool upwelled water, and cloudiness minimum due to the polar surges.

8.4.3. Surge of the Trades

1. Season and location
    a. winter, tropical continents.
    b. summer, southwest monsoon and oceanic trade wind regions.
2. Ahead of surge
    a. Trade wind inversion: Inversion usually lowers.
    b. Winds: Large vertical shear is present, with wind direction reversal between 500 to 400 mb level. For winter surges, base of the polar westerlies begins to rise.
    c. Pressure: No change in sfc pressure.
    d. Clouds: Typical daytime cloudiness is suppressed. About an hour before a strong surge occurs, small Cb's appear indicating the convergence occurring ahead of the surge line.
    e. Temperatures: No change in temperatures.
    f. Moisture: No change in depth of moist layer.
    g. Weather: Wx is better than usual.
3. Behind surge
    a. Trade wind inversion: Inversion rises or is even destroyed.
    b. Winds: Sfc wind speed increases; direction remains the same. For winter surges, polar westerlies often disappear and a rapid increase in depth of easterlies occurs.
    c. Pressure: Sfc pressure rises.
    d. Clouds: Several lines of Cb and Cu with showers, Cu, St, and Ac with rain.
    e. Temperatures: Temperatures throughout vertical fall.
    f. Moisture: Moist layer becomes very deep.

g. Weather: Rain showers, T-storms, and occasional severe wx occur along forward edge of surge; steady rain occurs for several hrs to several days behind forward edge.

4. End of surge
   a. Trade wind inversion: Inversion is reestablished.
   b. Winds: Sfc wind speed decreases to climatological normal.
   c. Pressure: Sfc pressure returns to climatological normal.
   d. Clouds: Occnl St or Sc formation at top of moist layer; otherwise cloudless.
   e. Temperatures: Sfc temperature returns to climatological normal. Upper troposphere warms and atmosphere increases in stability.
   f. Moisture: Moist layer becomes shallow near sfc with very dry air aloft.
   g. Weather: Wx "usually becomes very fine" (Institute of Tropical Meteorology 1945).
5. Notes
   a. Surges have been linked to the development of tropical cyclones, monsoon depressions, squall lines, equatorial convection, and the onset of El Niño.
   b. A surge is a sudden increase in the Hadley circulation, with increased convergence in the near-sfc layer and increased divergence in the upper troposphere. There is simultaneous interaction between the mid-latitudes and the tropics; researchers have not yet discovered the forcing mechanism.

8.4.4. Subtropical Cyclones

1. Season & location
   a. NH winter, 15°N to 35°N over North Pacific Ocean (kona storms)
   b. SW monsoon, eastern Arabian Sea (Arabian Sea cyclones)
   c. all seasons, North Atlantic Ocean.
2. Ahead of storm
   a. Trade wind inversion: Inversion height begins to rise and weaken; tropopause height begins to fall.
   b. Winds: Sfc winds are light. In sounding, see strong directional shear between lower and upper levels. Steering currents are weak.
   c. Pressure: Sfc pressure remains steady or rises slightly. In sounding, begin to see height depression and circulation above 700 mb.
   d. Clouds: Clouds are sct Cu, becoming stratiform at all levels.
   e. Temperatures: Sfc temps increase slightly or remain steady. Temps in lower troposphere (below 600 mb) begin to cool; temps in upper troposphere begin to warm.
   f. Relative humidity: Moisture inflow begins at all levels and becomes deeper in vertical.
   g. Weather: No significant wx.
3. During storm
   a. Trade wind inversion: Inversion is destroyed; tropopause height reaches minimum.

   b. Winds: Sfc winds remain light within 85 NM of storm center. Winds may gust from 20 to 40 kts in area 85 NM-270 NM from storm center. Steering currents remain weak. In North Atlantic, average maximum sustained sfc wind is 26 m/sec.
   c. Pressure: Low pressure center develops at sfc; in North Atlantic average minimum pressure is 996 mb. Largest pressure gradients, strongest winds, and greatest convergence are found in the 600-400 mb layer. There is upward motion above layer of max convergence and downward motion below it.
   d. Clouds: Clouds are stratiform at all levels with imbedded Cb. Ceilings 10,000-12,000 ft.
   e. Temperatures: Sfc temps are cooler due to evaporation. Temps in lower troposphere (below 600 mb) remain cooler than environment; temps in upper troposphere remain warmer.
   f. Relative humidity: Moisture inflow continues at all levels and reaches max depth in vertical.
   g. Weather: Wx is continuous mdt rain with periods of hvy rain and an occasional T-storm in the symmetrical area 85 NM-270 NM from storm center. Central core of storm has ovc As and lgt rainfall.
4. Behind storm
   a. Trade wind inversion: Inversion becomes reestablished; tropopause height rises.
   b. Winds: Sfc winds continue to be light. Wind gusts subside.
   c. Pressure: Sfc pressures begin to rise.
   d. Clouds: Clouds change from stratiform to cumuliform.
   e. Temperatures: Sfc temps begin to warm with cessation of rain. Warm advection occurs at upper levels.
   f. Relative humidity: Moisture advection stops with intrusion of dry air and depth of moist layer decreases.
   g. Weather: Wx regime changes from rain to showers.
5. Notes
   a. Most subtropical lows form from a closed upper-level low that gets cut off from polar westerlies; low lies south of subtropical ridge.
   b. Most subtropical lows form over water, although at least two lows have been documented as forming over land.
   c. Movement of low is very erratic–lows are as likely to move east as west, and have been known to loop aimlessly over the oceans.
   d. Because the low spends most of its life over water, it does not readily dissipate. The low center usually moves to a place where it is reabsorbed into the polar westerlies and loses its tropical characteristics. One to two lows per year in each basin develop warm-core characteristics and become tropical cyclones.

8.4.5. Temporales

1. Season & location
   a. wet; Pacific coast of Central America, most likely in Sep & Oct (avg. of 8/yr) with secondary max in Jun (avg of 4/yr).
   b. dry; Gulf of Honduras, most likely in Dec.
2. Formation
   a. Trade wind inversion: Inversion height begins to rise and weaken; tropopause height begins to fall.
   b. Winds: Sfc winds are light. In sounding, see strong vertical shear between low-level westerlies (due to monsoon trough surge (Pacific side) or polar surge (Caribbean side)) and upper-level trade wind flow from Caribbean. Steering currents are weak.
   c. Pressure: No noticeable change in sfc pressure. In soundings, begin to see all-layer depression above 700 mb. Storm center forms offshore.
   d. Clouds: Clouds at all levels become stratiform.
   e. Temperatures: Sfc temps increase slightly or remain steady. In soundings, begin to have cold pool in 300-200 mb layer (temp drops about 5°C).
   f. Relative humidity: Moisture inflow begins at all levels and becomes deeper in vertical.
   g. Weather: Wx is lgt steady rain.
3. During temporale (duration 1-3 days):
   a. Trade wind inversion: Inversion is destroyed; tropopause height reaches minimum.
   b. Winds: Sfc winds remain light within 85 NM of low center. Winds may gust from 20 to 40 kts in NE quadrant of storm (Pacific side). Steering currents remain weak.
   c. Pressures: Sfc pressures show little change. Storm center remains offshore. Vertical center is in mid to upper troposphere.
   d. Clouds: Clouds are stratiform at all levels with imbedded Cb. Ceilings 10,000-12,000 ft.
   e. Temperatures: Sfc temps are cooler due to evaporation. Upper-level cold pool persists.
   f. Relative humidity: Moisture inflow continues and moist layer reaches maximum depth.
   g. Weather: Wx is continuous mdt rain with periods of hvy rain; T-storms are rare. Rain can fall at the rates of 1-2 in/hr, 10 in/24 hr, and 15 in/36 hr. Flooding is a possibility, especially in areas that have no natural outlets for hvy precip and/or where rainfall is accentuated by orographic effects.
4. Dissipation
   a. Trade wind inversion: Inversion becomes reestablished; tropopause height rises.
   b. Winds: Sfc winds continue to be light. Wind gusts subside.
   c. Pressure: Sfc pressures show little change. Steering currents move storm slowly to NW (Pacific side). If storm moves onshore, it quickly weakens due to cutoff of moisture.

d. Clouds: Clouds change from stratiform to cumuliform.
e. Temperatures: Sfc temps begin to warm with cessation of rain. Warm air advection occurs at upper levels.
f. Relative humidity: Moisture inflow stops and depth of moist layer decreases.
g. Weather: Wx regime changes from rain to showers.

5. Notes
   a. Temporale usually begins with an initial area of instability caused by a stalled tropical depression or subtropical cyclone on Pacific side, cutoff low from a polar surge on Caribbean side. Circulation is reinforced with moisture inflow, along with monsoon trough surge or successive polar surges.
   b. In vertical, the temporale looks like a hurricane without the spiral bands.
   c. On Pacific side, higher pressures in subtropical ridge to NE can push the monsoon trough/temporale back into the Pacific.

8.4.6. Tropical Cyclones

1. Location & time of year
   a. western North Pacific from 180° to Asia; any month of the year, intensive period Jul-Nov.
   b. South China Sea; May-Dec, intensive period Jul-Sep.
   c. eastern North Pacific from Central American coast to 180°; May-Nov, intensive period Jul-Sep.
   d. western North Atlantic (west of 30°W) and Caribbean Sea; May-Dec, intensive period Aug-Oct.
   e. northern Indian Ocean (Arabian Sea and Bay of Bengal); any month of the year, intensive period May-Jun and Oct-Nov.
   f. western South Pacific (west of 130°W) and Australia; any month of the year, intensive period Dec-Apr.
   g. South Indian Ocean; Oct-May, intensive period Jan-Feb.
2. Outer circulation (36-90 hr before eye passage; 700-1600 km radial distance from eye)
   a. Winds: The upper tropospheric flow is predominantly anticyclonic; the anticyclonic effect can be seen at a distance of up to 1600 km for a mature cyclone. May have trough passage in upper troposphere.
   b. Temperatures: Sfc-500 mb temps show little change. Temps above 500 mb cool slightly. May see passage of upper cold low.
   c. State of the sea: The arrival of long sea swells with wave frequency of 2-4 per minute (average wave frequency is 10-15 per minute) begins when cyclone is 800 to 1600 km away. The direction from which the swell approaches indicates the direction of the storm:
      i. If the direction of the swell is constant, the storm will approach the area directly.
      ii. If the swell turns counterclockwise the storm will pass from right to left as seen by an observer facing the storm.
      iii. If the swell turns clockwise the storm will pass from left to right as seen by an observer facing the storm.

Abnormally high tides, particularly along the shore lines of partially enclosed bodies of water, indicate the presence of a tropical cyclone in the vicinity.

3. Moat (24-36 hr before eye passage; 400-700 km radial distance from eye)
   a. Trade wind inversion: Inversion lowers.
   b. Winds: Winds begin to curve cyclonically with time and have radial component towards cyclone center.
   c. Pressure: Little change in pressure.
   d. Clouds: Normal convective activity is suppressed. Ci is observed to be radiating from a point on the horizon in the general direction of the cyclone.
   e. Temperatures: Little change in sfc temps warm slightly. Upper-air temps above 500 mb begin to warm.
   f. Moisture: Mixing ratio very dry in vertical.
   h. Weather: There is prolonged suppression of convective activity, "unusually and exceptionally fine weather" in subsidence ahead of storm.
4. Outer rainbands (12-24 hr before eye passage; 200-600 km radial distance from eye)
   a. Trade wind inversion: Inversion rises.
   b. Winds: An approaching cyclone has sfc winds with speeds 25% or more above normal, flow curving cyclonically with time, and/or wind direction from a quadrant different from the normal flow. If cyclone is moving between W to NW, usual wind direction is N-NNE prior to passage of center. If cyclone is moving NE, usual wind direction is NNE-ESE prior to passage of center.
   c. Pressure: Sfc pressure begins to drop at the rate of 3 to 3.5 mb/24 hr. If sfc pressure values are 5 mb or more below normal, expect cyclone.
   d. Clouds: Cloud sequence is that expected for a warm-front passage in mid-latitudes: Ci followed by Cs and As overcast and Cb as outer rainbands approach. St, Sc, Cu and Cb in rainbands.
   e. Temperatures: Sfc temps fall in precip. Upper-air temps nearly constant.
   f. Moisture: Mixing ratio increases at all levels.
   h. Weather: Unusually heavy precipitation with Cs and As ovc is a predictor that cyclone is approaching rather than disturbance. Heavy showers and T-storms occur in the Cu congestus of the outer rainbands.
5. Inner rainbands, eyewall, eye (12 hr before to 12 hr after eye passage, up to 200 km radial distance from eye)
   a. Trade wind inversion: Inversion is destroyed.
   b. Winds: At sfc, winds above 33 m/sec (75 mph, 65 kts) signify an intense cyclone. Average maximum sustained wind speeds at sfc are 26 m/sec for tropical storms and 48 m/sec for hurricanes (North Atlantic). Wind speeds continue to increase toward the center of the cyclone. Strongest winds are on right side of cyclone when facing direction of motion (i.e. cyclone moving W will have strongest winds on N side). Max wind speeds occur in an annulus 5-10 NM wide corresponding with the eye wall cloud. In the eye, sfc wind speeds drop dramatically; after eye passage wind direction changes about 180° and wind speeds again reach a max. In vertical, have inflow layer from sfc to

25,000 ft, and outflow layer from 25,000 ft to 40,000 ft. Wind speeds are strongest in the sfc-3000 ft layer and then decrease with altitude.

c. Pressure: Tropical storm sfc pressures range from 980 mb to 1010 mb with an average minimum pressure of 999 mb (North Atlantic). Sfc pressure falls rapidly below 1000 mb for an intense cyclone; average minimum pressure is 969 mb (North Atlantic). Semi-diurnal cycle is detectable until steep pressure fall begins about 6-12 hours before passage of the cyclone center. Corresponding steep pressure rise means that cyclone center has passed.

d. Clouds: Convective clouds are arranged in spiral bands. Between the bands clouds are As and Ns from which light rain falls continuously. A dark wall of clouds, called the "bar" of the storm, mark the beginning of continuous rain squalls; it is the area where divergence changes rapidly to intense convergence. In the eye, clouds are sct to bkn As and Ac with thin ovc Ci and Cs; may see the sky in cloud breaks.

e. Temperatures: Sfc temps initially fall 2-3°C as rain begins and then become constant. Temps are below normal in rear of cyclone due to evaporation and sea surface upwelling. Upper-air temps (700 mb and above) are 10°C or more above normal, esp. in eye wall of mature cyclone. Tropopause breaks down and reforms above 100 mb.

f. State of the sea: Storm surge usually occurs near the eye of the cyclone, but sometimes make landfall before center passage. A cyclone with central pressure of 900 mb will have a rise in ocean surface of 1 m. Average surge height is 10-20 ft.

g. Weather: The sudden onset of heavy clouds and rain mark the edge of the cyclone proper. Heavy rain and strong winds occur with brief periods of light rain and winds. Eye of cyclone marked by dramatic drop in wind speed, thin ovc clouds with some breaks, little to no rain. After passage of eye, cyclone resumes full intensity of wind and rain.

6. Behind cyclone
   a. Trade wind inversion: Inversion becomes reestablished as outer spiral bands move off.
   b. Winds: Wind speeds slowly decrease to seasonal normal. Wind direction resumes normal quadrant.
   c. Pressure: Pressure increases rapidly and resumes semi-diurnal pattern.
   d. Clouds: Clouds reverse pattern noticed in approach of storm: Cb in outer spiral bands, then Ac and As to Cs and Ci. Convection is suppressed behind cyclone as it was suppressed ahead of cyclone.
   e. Temperatures: Temps show little change from normal. SST drops by 1-2°C due to upwelling.
   f. Weather: After main part of cyclone moves off, continue to have occnl showers in outer spiral bands. Weather becomes "very fine" again with nearly clear skies and suppressed convection for a day or so in the moat. Normal diurnal pattern then is reestablished.

7. Notes
   a. As a rule, tropical cyclones do not directly affect a station for more than two days.
   b. In-cloud lightning and/or T-storms within 150 km of cyclone center indicate cyclone is entering a period of intensification. T-storms are usually observed in outer spiral bands and during the decaying stage of the cyclone. Cyclones usually do not have T-storms in area of wind speeds over 60 mph.
   c. Microseismographs can distinguish the vibrations of a tropical cyclone, which have a period of 2-6 sec.
   d. Amount of precip is highly variable and the distribution of precip is asymmetric. If the cyclone is moving between west and north, heaviest precip is usually in left rear quadrant of direction of motion; if cyclone is moving northward, heaviest precip is usually in right front quadrant of direction of motion. Orographic effects will enhance precip amounts.
   e. Most regions of the tropical cyclone have a diurnal cycle in rainfall rate, with the maximum rate in early morning and minimum rate in late afternoon. The exception is for the inner-core regions (radius 111 km) of tropical cyclones with maximum sustained winds greater than 34 kts, which have a maximum rainfall rate in the evening.
   f. Greatest rainfall rates and most intense cyclones occur when SSTs are in the range 27°C-29°C.
   g. The greatest wind speeds, rainfall rates, and convective activity occur within the 111 km annulus surrounding the cyclone center.

8.5. Fog

8.5.1. Radiation fog

1. Time must be nighttime, usually near sunrise.
2. Skies must be clear.
3. Winds must be less than 3 m/sec.
4. Air temperature must be within 2°C of the dew point temperature. Fog more likely to occur if rain fell during the day.
5. Low-level inversion is present.
6. Fog more likely in mountain valleys when mountain wind is present.
7. Fog more likely in narrow river valleys because air becomes trapped and cools rapidly to dew point temperature.
8. Fog quickly dissipates a few hours after sunrise when air temperature begins to rise.

8.5.2. Advection fog

1. Time is usually late evening to mid morning, but may occur any time of day. Radiative cooling enhances development of advection fog.
2. Skies are usually clear over station. May observe low stratus deck over water.
3. Gradient wind direction is onshore; wind speed is not a factor.

4. Air temp falls and dew point temp rises to within 1°C of SST. Fog develops when the dew point temp is equal to SST. Fog more likely to occur if rain fell recently.
5. Low-level inversion is present.
6. Drizzle or lgt rain may occur with fog.
7. Fog is likely over coastal areas where upwelling is present offshore. During winter and spring seasons, fog is likely on the east coast of continents when tropical maritime air moves over relatively cold coastal waters.
8. Fog may lift to low stratus or even break up because of daytime heating, but will return again at night if advection is still occurring. Fog regime will end when advection ends.
9. Fog may occur with sea breeze front if fog developed offshore during night and is advected onshore with sea breeze.

8.5.3. Upslope fog (mountain stations)

1. Time is usually nighttime to mid-morning, but may occur any time of day. Radiative cooling enhances development of upslope fog.
2. Skies are usually clear over station.
3. Gradient wind direction is upslope; wind speed is not a factor.
4. Temp (due to adiabatic expansion) and moisture increase with elevation. Fog more likely to occur if rain fell recently.
5. Low-level inversion is present.
6. Drizzle or lgt rain may occur with fog.
7. Fog is frequent on windward side of slopes and at higher elevations.
8. Upslope fogs are deep and show little diurnal variation. Fog regime will end when upslope wind ends.

8.6. Abbreviations

Ac	altocumulus
As	altostratus
bkn	broken
°C	degrees Celsius
Cb	cumulonimbus
Ci	cirrus
Cs	cirrostratus
Cu	cumulus
deg	degrees Kelvin
E	east
ENE	east-northeast
ESE	east-southeast
Fr	Froude number
FROPA	frontal passage
ft	feet
g	grams
hr	hour
hvy	heavy
in	inches
ITCZ	Intertropical Convergence Zone
K	degrees Kelvin
kg	kilograms
km	kilometer
kts	knots
lgt	light
LST	local standard time
m	meter
max	maximum
mb	millibar
mdt	moderate
mi	miles
min	minimum
mph	miles per hour
N	north
NE	northeast
NH	Northern Hemisphere
NM	nautical mile
NNE	north-northeast
NNW	north-northwest
Ns	nimbostratus
NW	northwest
ovc	overcast
precip	precipitation
rad	radians
S	south
Sc	stratocumulus
sct	scattered
SE	southeast
sec	second
sfc	surface
SH	Southern Hemisphere
SSE	south-southeast
SST	sea surface temperature
SSW	south-southwest
St	stratus
SW	southwest
temps	temperatures
T-storms	thunderstorms
TUTT	Tropical Upper-Tropospheric Trough
W	west
WNW	west-northwest
WSW	west-southwest
wx	weather
yr	year